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PHYSIOLOGICAL RESPONSES TO A PROTOTYPE HYBRID AIR-LIQUID MICROCLIMATE COOLING SYSTEM DURING EXERCISE IN THE HEAT

U S ARMY RESEARCH INSTITUTE
OF
ENVIRONMENTAL MEDICINE
Natick, Massachusetts

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The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy or decision unless so distinguished by other official documentation.

Human subjects participated in these studies after giving their informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers on Research.

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TECHNICAL REPORT

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PHYSIOLOGICAL RESPONSES TO A PROTOTYPE HYBRID AIR-LIQUID MICROCLIMATE COOLING SYSTEM DURING EXERCISE IN THE HEAT

by

Bruce S. Cadarette, Andrew J. Young, Barry S. DeCristofano,
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March 1988

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and

U.S. Army Natick Research, Development and Engineering Center

Natick, Massachusetts 01760-5007

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ABSTRACT

The effectiveness of a prototype air-liquid hybrid microclimate cooling system was compared to previously developed air- and liquid-cooled systems to assess heat stress reduction during physical exercise. This hybrid system could be used by combat vehicle crewmen needing both types of cooling for mounted and dismounted activities. Five heat acclimated men performed four experiments of 120 minutes of treadmill walking at a metabolic rate of 332 watts in a hot (37.7°C T_{db}, 11.5°C T_{dp}) environment. The system configurations were air (A) and hybrid-air (HA) both with mean inlet temperatures of 28°C T_{db}, 16°C T_{dp} and flow rates of 4.72 $l \cdot sec^{-1}$ (10 $ft^3 \cdot min^{-1}$), liquid (L) and hybrid-liquid (HL) both with mean inlet temperatures of 25°C and flow rates of $6.3 \cdot 10^{-3}$ $l \cdot sec^{-1}$ (50 $lbm \cdot hr^{-1}$). These systems were worn under MOPP IV protective garments. Endurance time (ET), whole body sweating rate (SR), heart rate (HR), mean weighted skin temperature (T_{sk}) and rectal temperature (T_{re}) were measured. Subjective assessments of perceived exertion and thermal sensation were also obtained. All subjects completed the 120 minutes of exercise with all four microclimate cooling systems. There were no differences between systems for either SR, final exercise T_{re}, or final HR. HR did increase during exercise ($p<0.05$) with both the L and HL systems. Final T_{sk} with the HL system was higher ($p<0.05$) than with all other systems, and ΔT_{re} with the HL system was greater than with the A system. There were no differences at any time in the subjective measurements. These data demonstrate that the prototype air-liquid hybrid microclimate cooling system allowed the same ET as the A and L systems. However, the small but

significantly greater thermal strain shown with the HL configuration relative to the A system indicates a potential need for an alteration in the amount of cooling provided for the HL configuration, as it had the lowest calculated cooling capacity of all the systems.

INTRODUCTION

The insulation and low moisture permeability of chemical protective clothing severely limit the body's normal heat dissipating mechanisms, most markedly by reducing sweat evaporation. The presence of this heat stress problem has been documented over many years (6,7,15,16). Tolerance time of soldiers performing moderate work in hot environments while wearing protective clothing may be limited to about 60-90 minutes (4,5). This heat stress problem has led to the development of a number of different microclimate cooling systems (cooling the environment immediately adjacent to the skin), reported to be effective in alleviating heat stress and extending performance (8,9,11,12,14,15,16,17).

While the most effective microclimate cooling system would cover the entire body (13,17), practical constraints on system design often allow selected cooling of only limited areas. It has been demonstrated in a number of studies that even with cooling only limited parts of the body, sufficient heat can be removed to alleviate heat strain and extend performance time (8,9,13,14,18).The Individual Protection Directorate (IPD), US Army Natick Research, Development, and Engineering Center (NATICK) has undertaken a systematic program to develop microclimate cooling systems for soldiers wearing protective clothing.

IPD has developed an air-cooled microclimate system which blows cooled air across the back, chest and neck with the additional capability of blowing air to the facepiece of the gas mask worn in MOPP IV configuration. This vest has

been tested under controlled laboratory and field conditions and provides adequate cooling for extended performance relative to no cooling when dressed in MOPP IV (2,11). IPD has also developed a liquid cooled vest which would be more feasible for use by a dismounted crewman working outside his vehicle. The liquid cooled system would allow carrying some type of heat sink to dissipate heat removed by conduction through the vest. This vest has also been shown to provide adequate cooling for extended performance when tested in controlled conditions along with the air-cooled system (11).

While the two systems (air- and liquid-cooled vests) both provide sufficient protection from thermal strain for vehicle crewmen, it could provide a logistical problem were it deemed appropriate that both systems be available for crewmen. With this in mind IPD developed a garment compatible with both air and liquid cooling modes. The purpose of this study was to compare the cooling provided by the hybrid vest with the cooling provided by the current air-cooled and liquid-cooled vest systems.

METHODS

Five male soldiers volunteered as test subjects after being informed of the purpose and procedures of the study, any known risks and their right to terminate participation at will without penalty. Each expressed understanding by signing a statement of informed consent.

The subjects had their height and weight measured, and their per cent body fat estimated by measuring skinfold thickness at four sites (3). The study was conducted in July in Natick, Massachusetts. While it was assumed that

subjects would be naturally heat acclimated at this time of the year, they did participate in a four day heat acclimation program prior to the beginning of experimental testing. Each day the subjects walked on a level treadmill at 1.34 $m \cdot s^{-1}$ for 180 minutes (three repeats of 10 minutes rest, 50 minutes exercise) in a 38°C T_{db}, 12°C T_{dp} environment. During acclimation all subjects wore shorts and tennis shoes.

Following acclimation all subjects completed four heat stress tests consisting of 150 minutes total exposure (three repeats of 10 minutes rest, 40 minutes treadmill walking) in a 37.7°C T_{db}, 11.5°C T_{dp}, 1.12 $m \cdot s^{-1}$ wind speed environment. In all heat stress tests, subjects wore a t-shirt, cooling vest, combat vehicle crewman (CVC) fragmentation protective vest, CVC Nomex coveralls, chemical/biological (CB) overgarment (pants and jacket), M-17 gas mask, butyl rubber hood, CB butyl rubber gloves with cotton liners and CB butyl rubber overboots (estimated clo=2.75, I_m=0.30). Helmets were not worn. The filter elements were removed from the masks to facilitate breathing. On one day each subject wore the currently fielded NATICK air-cooled vest (A) without benefit of facepiece cooling. On one day each subject wore the most current model of the NATICK liquid-cooled vest (L). On one day each subject wore the experimental hybrid vest in the air-cooled mode (HA). Finally, on one day each subject wore the experimental hybrid vest in the liquid-cooled mode (HL).

The NATICK air-cooled vest and the air-cooled mode of the hybrid vest were engineered to distribute conditioned air at 4.72 $l \cdot sec^{-1}$ (10 $ft^3 \cdot min^{-1}$) with a mean inlet temperature of 28°C T_{db}, 16°C T_{dp}. Under these conditions and with an assumed subject skin temperature of 35°C it is calculated that the

air-cooled vests could provide a theoretical maximal cooling of 400 watts. It is not possible to calculate the actual cooling provided by the air cooled vests as the air is dissipated through the uniform once it cools the body surface. The NATICK liquid-cooled vest and the liquid-cooled mode of the hybrid vest were engineered to provide cooling with a flow rate of $6.3 \cdot 10^{-3}$ $l \cdot sec^{-1}$ (50 $lbm \cdot h^{-1}$) with a mean inlet temperature of $25^{O}C$. Under these conditions and with an assumed subject skin temperature of $35^{O}C$ it is calculated that the liquid-cooled vests could provide a theoretical maximal cooling of 253 watts. Actual mean cooling rates calculated from flow rate, coolant heating capacity and coolant temperature change were 93($\pm$10) watts for the NATICK liquid cooled vest and 85($\pm$12) watts for the liquid-cooled mode of the hybrid vest. Cooling systems were presented to the subjects using different orders of presentation to help eliminate experimental bias. A full description of the microclimate cooling systems used is given in Appendix A.

During all heat exposures, both acclimation and stress tests, the subjects inserted a rectal thermister 10 cm beyond the anal sphincter, used to measure core temperature (T_{re}), both for the subjects safety and for experimental data. Additionally, in all heat exposures, heart rate was determined from electrocardiograms obtained from chest electrodes (CM5 placement) telemetered to and continuously displayed on an oscilloscope cardiotachometer unit. The heart rate (HR) data was also used both to monitor subject safety and for experimental data. On the heat stress test days, all subjects additionally were fitted with a three site (arm, chest, leg) thermocouple harness to measure skin temperature. Mean weighted skin temperatures T_{sk} were calculated from these measurements to evaluate effectiveness of the various cooling vests. Subjects

were required to break the integrity of their gas masks once during each walk of the four heat stress test days in order to breathe into a mouthpiece for the collection of expired gases. Expired gases were collected in 100 liter Douglas bags and were analyzed for ventilatory volume, and per cent carbon dioxide and oxygen in order to determine the metabolic rate elicited by exercise with each cooling system. During the tests all subjects were allowed to drink water ad libitum through a plastic drinking straw inserted under the gas mask. All water intake was measured and whole body sweating rate (SR) was calculated on all subjects from nude weight changes corrected for water intake. Subjects were also asked for subjective ratings of perceived exertion (1) and thermal sensation (18) using standard scales.

Analyses of variance for repeated measures were used to compare variables of T_{re},T_{sk} and HR at the completion of each exercise bout as well as performance time and SR for each test day. Tukey's test of critical differences was used where appropriate. All differences are reported at $p<0.05$, unless otherwise noted.

RESULTS

The mean ($\pm$ standard deviation) subject age was 24 ($\pm$5) years, height was 175 ($\pm$4) cm, weight was 66 ($\pm$12) kg, Dubois body surface area (A_D) was 1.79 ($\pm$0.16) m^2, $A_D \cdot mass^{-1}$ was 2.76 ($\pm$0.27) and body fat was 15.8 ($\pm$6.7)per cent.

The subjects metabolic rate during exercise was 332 watts and found to be consistent throughout the four heat stress tests. All subjects completed the entire 150 minute exposure time in all heat stress tests. There was no

significant difference in the subjects' final T_{re} at the completion of each experiment among the vests. The subjects' mean final T_{re} value for all heat stress tests 37.7°C. When the subjects' change in core temperature (ΔT_{re}) was calculated from initial and final exercise core temperature values, there was no significant difference between the A and HA vests nor was there a difference between the L and HL vests. However, the increase in T_{re} during exercise with the HL vest(0.87°C) was significantly greater ($p<0.05$) than the increase during exercise with the A vest(0.46°C). There were also significant differences for final exercise T_{re} between bouts with each cooling vest. Final exercise T_{re} increased significantly ($p<0.05$) between bout 1 and bout 3 with each vest, between bout 1 and bout 2 with all vests except the HA vest, and between each bout with the L vest (Figure 1).

The subjects' final exercise T_{sk} value was significantly higher (36.6°C) with the HL vest than with the L vest (34.7°C). This pattern was consistent throughout the heat stress tests as the subjects' T_{sk} value with the HL vest was significantly higher than not only with the L vest, but with all the other vests at the end of each exercise period (Figure 2). There was no significant difference in the subjects' T_{sk} values between the A and HA vests at any time during the heat-stress tests.

Final HR values did not show any significant difference among the vests, with a mean value of 135 $b \bullet min^{-1}$ for all heat stress tests. However, there were significant increases in HR between the end of the first exercise bout and the end of the third exercise bout for both the L vest ($\Delta HR=14$ $b \bullet min^{-1}$) and the HL vest ($\Delta HR=19$ $b \bullet min^{-1}$) (Figure 3). There was no significant difference in SR among the vests with a mean value of 13.4 $g \bullet min^{-1}$.

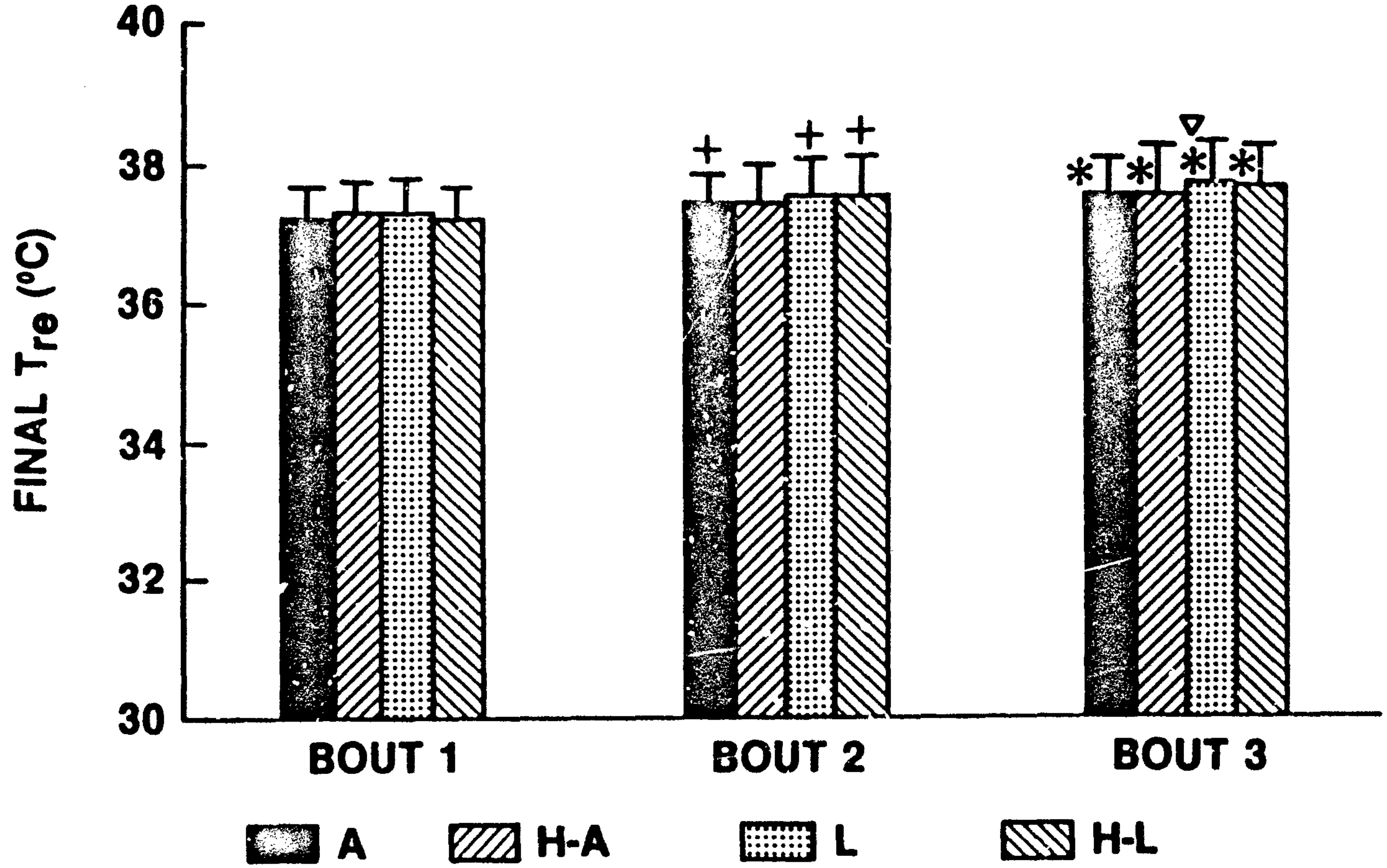

Figure 1. Mean core (rectal) temperatures at the end of each exercise bout with the four microclimate cooling systems. +Bout 2>bout 1; *bout 3>bout 1; ∇bout 3>bout 2 ($p<0.05$).

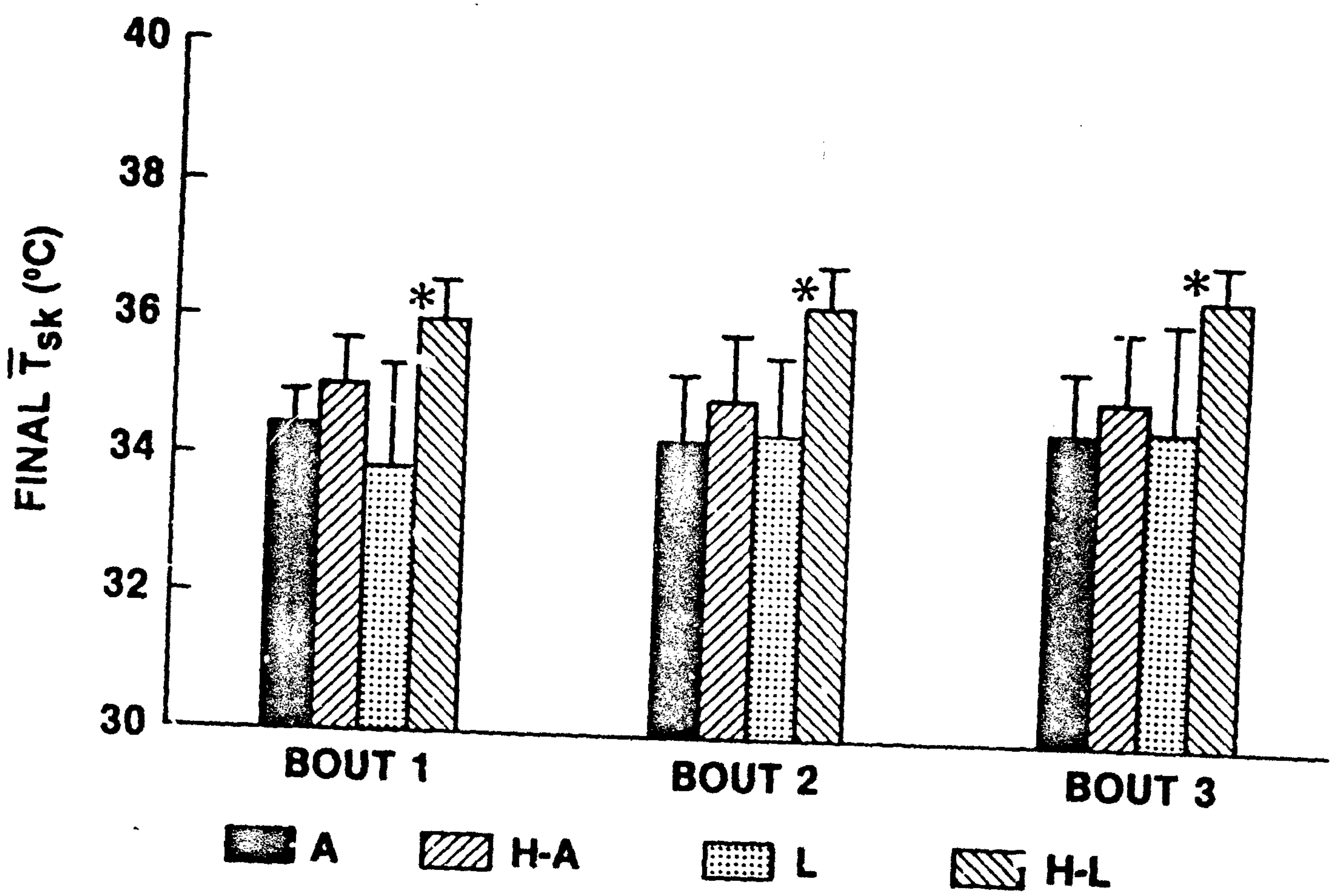

Figure 2. Mean weighted skin temperatures at the end of each exercise bout with the four microclimate cooling systems. *Greater than all other vests ($p<0.05$).

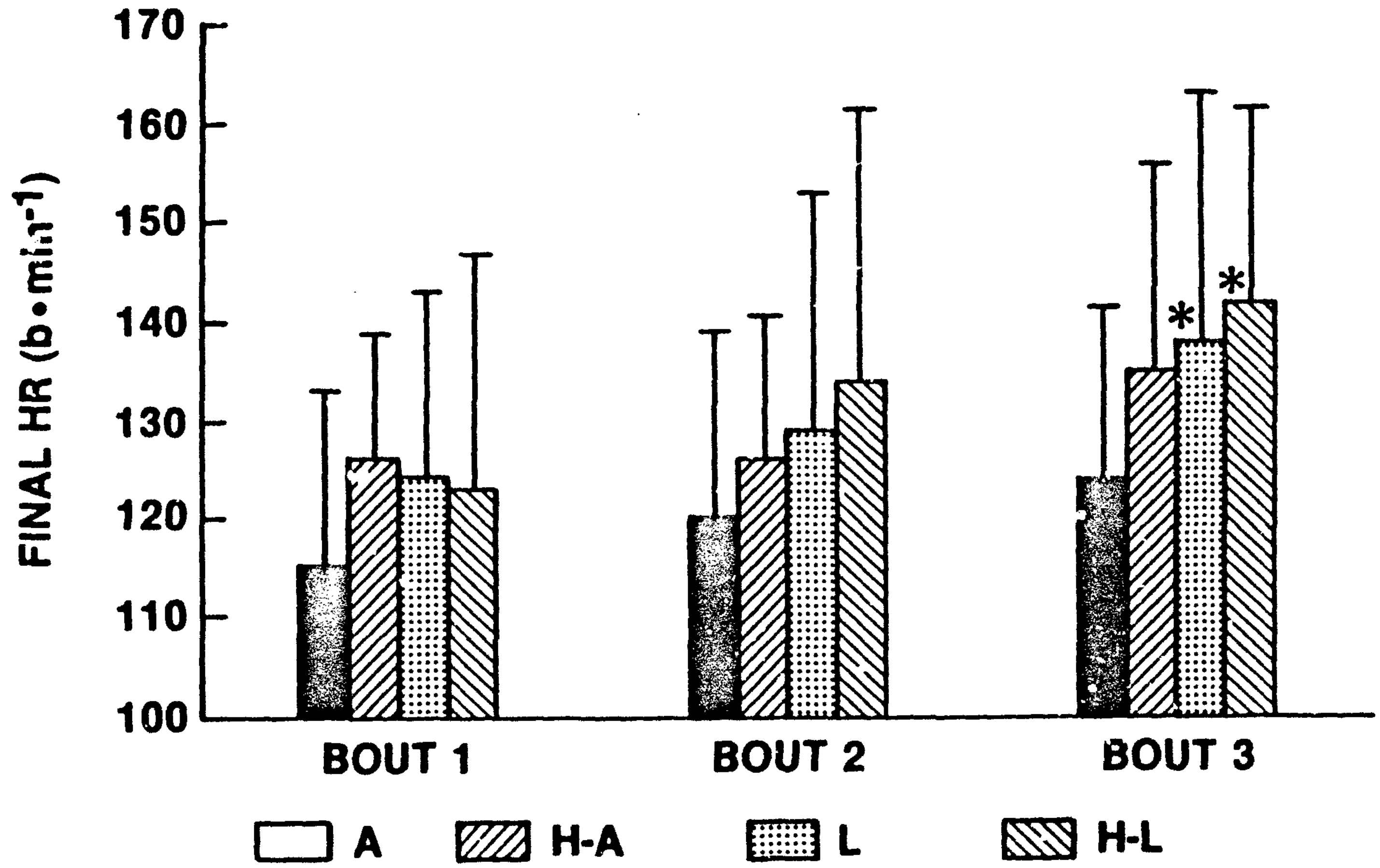

Figure 3. Mean heart rates at the end of each exercise bout with the four microclimate cooling systems. *Bout 3>bout 1 ($p<0.05$).

The subjective evaluations for perceived exertion showed no significant differences at any time during any of the heat stress tests. The subjects rated the exercise sessions with a mean value of 12.2 or a "light" exercise session. Likewise, the subjective evaluations for thermal sensation showed no significant differences at any time during any of the heat stress tests with a mean value of 5.2 or a perception of feeling warm.

DISCUSSION

The necessity of some form of microclimate cooling for combat vehicle crewman is a clear cut issue, as soldiers forced to remain in a MOPP IV configuration in a hot environment will reduce their work preformance (4,5,11). This need has been adequately answered by IPD in the form of the air-cooled vest which is effective when worn by crewmen in vehicles with conditioned air. These vests are light and non-restrictive for the wearer. The liquid-cooled vest developed by IPD addresses the problem of cooling when crewmen are disconnected from their vehicle's cooling umbilical system, such as during reload, refuel operations. The liquid-cooled vest is somewhat bulkier and more restrictive than the air-cooled version, but does allow for carrying a portable heat sink to dissipate the heat carried away from the body through the liquid channels. The hybrid vest examined in the current investigation attempts to incorporate the best qualities of both currently existing vests, and provide adequate cooling.

Under the exact conditions used in this study, the prediction model developed by USARIEM (10) indicated that with no microclimate cooling, but maintenance of adequate hydration, subjects would have reached an elevated

core temperature of 39.5°C after 124 minutes of continuous work. In the present study, all subjects completed the 150 minute exposures with a mean core temperature of 37.7°C for the four cooling configurations. The HA vest proved to be equally effective as the A vest at preventing the rapid increase in core temperature. Subjectively, the subjects initially complained of feeling uncomfortable, and hotter in the bulkier HA vests, than they did when starting exercise in the A vests. While some feeling of discomfort remained throughout the exercise in the hybrid vest, ratings of perceived exertion, and thermal sensation in addition to the actual physiological data indicated that the HA vest did an adequate job with no distinguishable difference between it and the A vest.

The HL vest also served to provide adequate cooling so all subjects could complete their exercise exposure without approaching the 39.5°C cutoff point. In fact, as was the case with the air vests, there was no distinguishable difference in the final core temperatures between the HL vest and the L vest. However, when examining the change in core temperatures of all the vests over the course of an entire experiment, the HL vest did not match the performance of the A vest. Additionally, while not significantly different from the A vest the subjects did have the second largest ΔT_{re} (0.67°C) with the L vest. These results were not totally unexpected, because of the lower theoretical cooling capacities with the liquid-cooled vests (253 W) relative to the air-cooled vests (400 W). While the differences were minor under the constraints of these experiments, they could be magnified if environmental conditions were more extreme, or individuals performed exercise at a higher metabolic rate.

While placement of chest thermocouples relative to the cooling channels could skew the results, the mean weighted skin temperature values did indicate a higher skin temperature under the HL vest than with all the other vests. This would result in a smaller temperature gradient between the blood flowing beneath the skin and the vest, and therefore the possibility of less heat being removed by the liquid flowing through the vest for a given skin blood flow. As a result a greater cutaneous blood flow would be needed to dissipate a given amount of heat. Both the HL vest and the L vest also showed increases in the subjects' final heart rate values between the end of the first and third exercise bouts. This could indicate that there was an increasing cutaneous vasodilation and compliance to allow for a greater skin blood flow and volume to enable conductive heat loss when wearing a liquid cooling system. This greater redistribution of blood to peripheral circulation would result in a high heart rate to meet both the metabolic and cooling demands.

CONCLUSION

It appears that while there are problems with comfort and design in the hybrid vest, in general it compares favorably with both the A vest and the L vest in reducing heat strain. However, while subjects were provided sufficient cooling to stay well within safety guidelines there were some minor differences between vests with the liquid-cooled mode of the hybrid vest showing the weakest performance. Some of these differences may be resolved by changing the liquid flow path in the hybrid vest. Other differences in physiological response between air-cooled and liquid-cooled vests, may possibly be reduced by increasing flow rates or reducing liquid temperature delivered to the liquid-

cooled vests. It may also be that the performance differences between the vests is insignificant for the duration that the liquid-cooling vests will be needed.

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APPENDIX A

1. Vest, Microclimate Cooling: Air, NSN 8415-01-27-5634

The vest is designed to provide chest, neck and back cooling via a hose and manifold system mounted on an open weave fabric. The hoses are lightweight, crush resistant and maintain a constant inside diameter upon bending. Air from a blower is delivered to the vestaand distributed in proportions of approximately 40% to the chest and back and 20% to the neck. The vest is lightweight (0.45 kg) and offers low resistance to air flow. It is worn over the undershirt and beneath the fragmentation protective vest. The chest manifold distributes the air directionally through four holes for chest cooling. Approximately two-thirds of the air flow continues through two hoses containing holes for cooling the neck. These hoses lead to a circular manifold where the remaining air is spread across the back through 10 holes on the perophery of the manifold. The vest provides a one inch space around the trunk.

2. Liquid Microclimate Cooling Garment

The liquid cooling garment is constructed of polyurethane-coated nylon,and uses a diffuse flow pattern. Chilled liquid enters at the back of the collar and flows in parallel to each side of the chest, over the shoulders to the lower back and then up the back to an exit port located just below the collar. A 10% propylene glycol and water solution is used as a coolant.

3. Hybrid Microclimate Cooling Garment

The hybrid microclimate cooling garment consists of two parallel circuits, one for air and the other for liquid. Two layers of polyurethane-coated nylon, heat sealed into panels, form a continuous channel through which the chilled liquid is circulated. The coolant flows in series from the front-right torso region, to the back, to the front-left torso, and then doubles back along the opposite route. The concept behind this layout is to eliminate a "cold" region at the vest inlet and a "hot" region at the vest outlet. Turning the flow channel back along a parralel route provides an averaged coolant temperature to the skin. A 10% propylene glycol and water solution is used as coolant. Air cooling is introduced by the incorporation of perforated tubes between the straight portions of the liquid channel. Two tubes are located over the wearer's chest and three over the back.

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